

Advanced Numerical Methods for NWP Models

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LONG-TERM GOALS

The long-term goal of this research is to construct the Navy's next-generation global numerical weather prediction (NWP) model using new numerical methods specifically designed for distributed-memory and vector computers. To distinguish it from the current Navy global atmospheric model, the navy Operational Global Atmospheric Prediction System (NOGAPS), we shall refer to this new model as the Navy's Spectral Element Atmospheric Model (NSEAM). To take full advantage of distributed-memory computers, the spherical global domain of NSEAM is partitioned into local sub-domains, or elements, which can then be solved independently on multiple processors. The numerical methods used on these sub-domains must be not only local in nature but also high-order accurate and highly efficient. Thus, NSEAM is being constructed so that it is as accurate as the current spectral model (NOGAPS); is more efficient, thereby allowing for finer resolution forecasts; and is geometrically more flexible, thereby allowing for the use of adaptive or telescoping grids. This will allow for better coupling with mesoscale models and eventually perhaps allowing for a modeling paradigm whereby the global and mesoscale models are either unified or at least share the same numerical algorithms which facilitates their maintenance.

OBJECTIVES

The objective of this project is to construct new high-order local methods for the Navy's next-generation global NWP model. The high-order accuracy of these methods will ensure that the new model yields the same accuracy as the current spherical harmonics model while the locality of these methods will ensure that the efficiency of the model increases as the number of processors increases.

APPROACH

To meet our objectives we explore:

1. spectral element (SE) and discontinuous Galerkin (DG) methods on quadrilateral and triangular grids,
2. semi-implicit (SI) and semi-Lagrangian (SL) time-integrators, and
3. adjustments to the physical parameterization and non-reflecting boundary conditions of the current NOGAPS to incorporate it into NSEAM.

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The power of SE and DG methods is that they are high-order accurate, like spherical harmonics methods, yet are completely local in nature – meaning that the equations are solved independently within each individual element and processor. Furthermore, high-order methods have minimal dispersion error which is an important property for capturing fine-scale atmospheric phenomena (e.g., tropical cyclones, Kelvin and Rossby waves). In addition, SI and SL methods offer vast improvements in efficiency due to the longer time steps that they permit.

After validation of the SE, DG, SI, and SL discretization on barotropic test cases, the full 3D adiabatic (dry physics) hydrostatic primitive equation model was closely scrutinized. The SI time-integrator of NSEAM was ported to the message-passing interface (MPI). At this point direct comparisons with the current version of NOGAPS were made. Superior performance of NSEAM over NOGAPS then justified the further effort into taking the steps to make NSEAM the next operational NWP model. In order to accomplish the final objective, the following steps must be accomplished:

1. the NOGAPS physical parameterization package must be modified and then coupled with the NSEAM dynamical core,
2. non-reflecting boundary conditions need to be added to NSEAM in order to avoid spurious wave reflections emanating from the orography, and
3. development of the tangent linear and adjoint models of NSEAM to be used for both data assimilation and sensitivity studies.

WORK COMPLETED

NSEAM Scalability. The superior performance of the semi-implicit NSEAM were published in the July B 2005 issue of the Quarterly Journal of the Royal Meteorological Society (Ref. [4]) which showed that at T239 L30, NSEAM dynamics is 60% faster than NOGAPS dynamics, and that at T498 L60 NSEAM scales linearly – a feat unequaled by spherical harmonics and most newly-proposed next-generation models (see Fig. 1).

NSEAM Numerics. The DG method on triangular grids was developed (see Ref. [2]) which shows that this method is capable of handling sharp discontinuities (such as shocks) which then makes it the leading candidate for resolving all types of mesoscale phenomena. In addition, a new semi-implicit Lagrangian time-integrator has been developed (see Ref. [1]), which we will now begin testing on NSEAM; this new time-integrator should allow larger time-steps to be used which will result in a further increase in efficiency.

Non-reflecting Upper Boundary Conditions. Non-reflecting upper boundary conditions must be implemented within NSEAM in order to avoid vertically propagating gravity waves emanating from the orography to reflect downward from the model top and then contaminating the solution. From the various choices available, it was determined that using the conventional approach of using sponge layers which applies Rayleigh friction to the surface layers and Newtonian cooling to the top layers would result in the fastest working model. This sponge has now been added to NSEAM and testing of the sponge layer has begun. To test the effectiveness of the sponge, we have added analytic mountains in order to simulate real waves. To increase the effectiveness of the sponge, we have increased the model layers to 48 but expect to further increase it to 60 in 2006.

Physical Parameterization. A majority of the time in this project this year has been spent on coupling the NSEAM dynamical core with the current NOGAPS physical parameterization routines (called DIABAT). Various interfaces have had to be constructed in order to allow both of these quite different models to work in unison. For example, NSEAM relies on Cartesian coordinates to allow for any grid to be used whereas DIABAT assumes spherical coordinates. Thus a very accurate way of mapping from Cartesian to spherical coordinates had to be developed. This transformation is not as straightforward as one might think due to the singular nature of trigonometric functions near the poles. With this transformation developed, NSEAM uses Cartesian coordinates for the dynamics, maps to spherical coordinates for the physics (DIABAT), and then maps back to Cartesian for the remainder of the operations.

Another challenge with including DIABAT within NSEAM is that the logic of these two routines is vastly different. For example, NSEAM is written in a general way using indirect addressing which allows for any grid geometry to be used. However, DIABAT is written in a logically Cartesian way where there is an “I” and “J” direction; this is called direct addressing. Direct addressing is typical of structured grid codes whereas NSEAM is written for fully unstructured grids and thereby has no direction. This incompatibility between the two codes has required a careful modification of some portions of the DIABAT code which we describe in the results section.

RESULTS

NSEAM Scalability. In Ref. [4] we show that NSEAM scales extremely well for increasing processor count, especially as the resolution is increased. Fig. 1 shows that at T249 L30 and using a time-step of 300 seconds, NSEAM achieves over 60 simulation days per wallclock hour for 386 processors. However, it is evident from Fig. 1a that the performance of NSEAM T249 L30 is beginning to peak. Increasing the resolution to T498 L60 with a time-step of 150 seconds increases the problem size by a factor of 16 (a factor of 4 in the horizontal, a factor of 2 in the vertical, and another factor of 2 in time); however, Fig. 1b shows that NSEAM T498 L60 achieves over 7 simulation days per wallclock hour for 386 processors. Thus the performance has only decreased by a factor of 8 even though the problem size has increased by a factor of 16. Furthermore, NSEAM has scaled linearly (perfectly) at T498 L60.

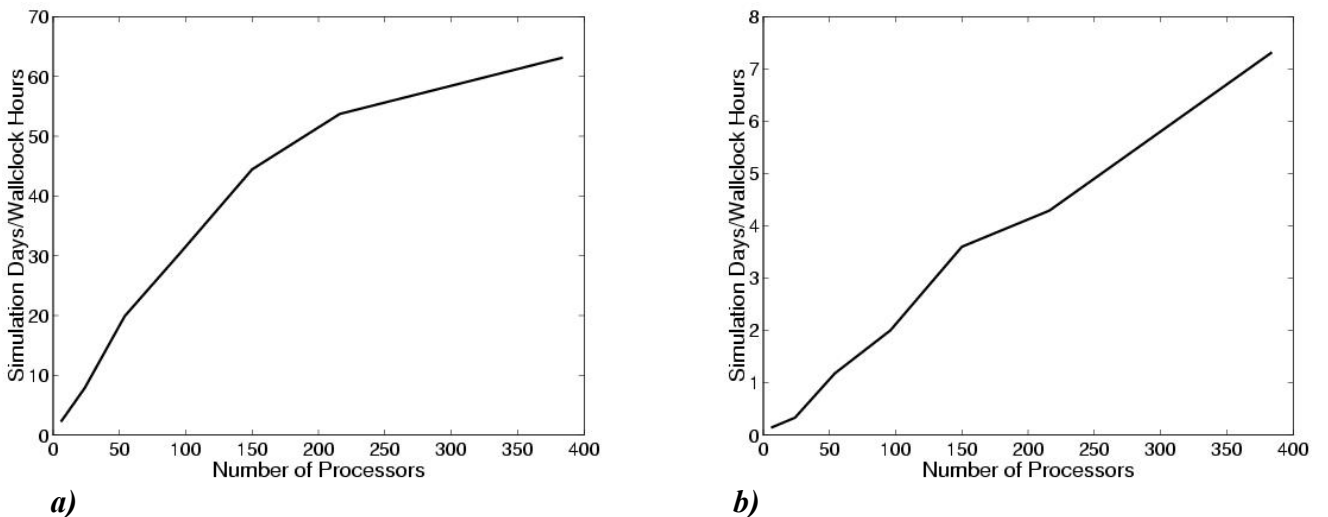


Figure 1: Scalability of NSEAM on an IBM SP4 with resolution a) T249 L30 and b) T498 L60.

NSEAM Numerics. To show the advantages of using the new Lagrangian semi-implicit time-integrator that we developed in Ref. [1] in Fig. 2, we show error norms as a function of Courant number which in turn, is a function of time-step; thus a large Courant number signifies a large time-step. Thus in these figures, the Eulerian semi-implicit time-integrator developed previously in Ref. [4] can only use Courant numbers less than 3, which is the first point on the left in Figs. 2a and 2b. The new time-integrator, which we call HELSI (Hybrid Eulerian-Lagrangian Semi-Implicit), combines the semi-Lagrangian (SL) and operator-integration-factor splitting (OIFS) methods into a unified formulation. From Fig. 2 one can see that both methods yield very good error norms for Courant numbers up to 15; in other words, we have been able to increase the time-step by a factor of 5 from the Eulerian semi-implicit method without incurring large errors. While this magnitude of increased time-step may not be realistic for more complicated flow problems (with terrain and highly nonlinear effects) even a modest time-step increase of a factor of 2 is sufficient to make the new approach worthwhile. Tests on more complicated flows will be reported on in an upcoming journal article currently being written.

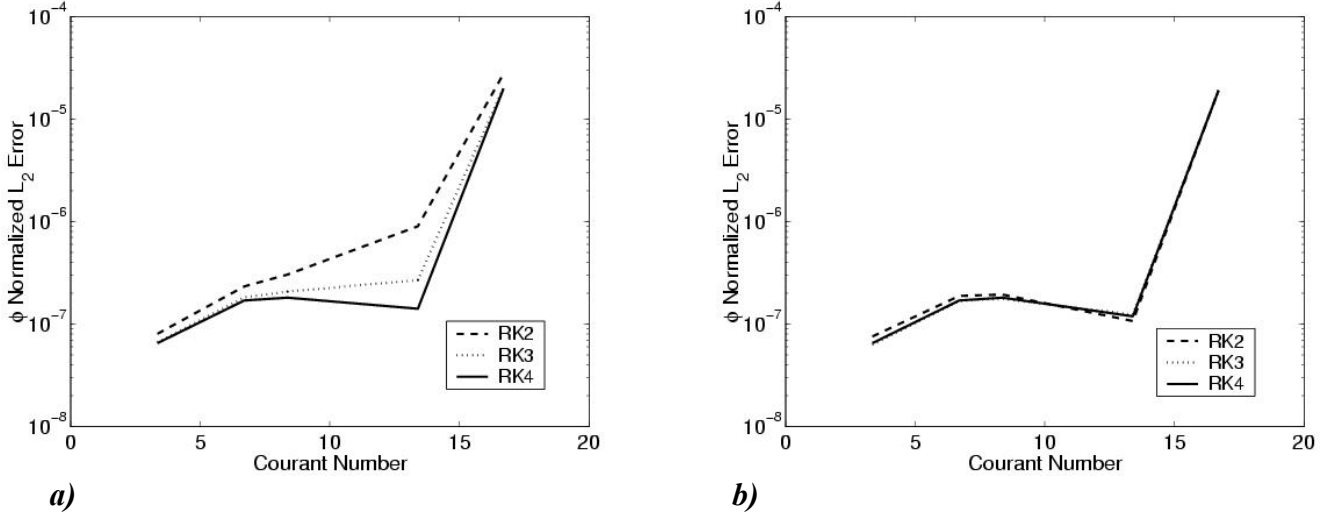


Figure 2: Error as a function of Courant number for the new time-integrators using a) the semi-Lagrangian (SL) and b) the operator-integration-factor splitting (OIFS) methods.

Physical Parameterization. To elegantly splice DIABAT and NSEAM it has been critical to modify some portions of the DIABAT code, in addition to constructing interface routines. The difficulty stems from the vastly different formulations of structured and fully unstructured grid codes. Specifically, because DIABAT assumes a latitude-longitude grid, which is a logically Cartesian grid, it expects the data to be ordered in an I (longitude) and J (latitude) direction. Thus the point I-1 and I+1 of any variable F will be the left and right neighbors of the point I; this is an example of direct addressing. In contrast NSEAM has no I and J directions and so the function value F at I+1 may not lie next to the function value F at I. Thus, NSEAM is written in a very general way which does not assume any direction and for this reason it can use any grid; this is a significant advantage if one expects to use adaptive or fully unstructured grids.

At this point, we have begun modifying **do loops** inside of DIABAT that look like this:

```
Do J=1,...,JM
Do I=1,...,IM
F(I,J)=Some Operation    (DIRECT ADDRESSING)
END
END
```

To loops that look like

```
Do K=1,...,NPOIN
F(K)=Some Operation      (INDIRECT ADDRESSING)
END
```

Where IM and JM are the number of points in the longitude and latitude in a lat-lon grid and NPOIN is the number of total points in the horizontal (latitude and longitude but in an unstructured ordering).

Finally, to avoid too much modification of both the NSEAM and DIABAT codes it was determined that constructing DIABAT as a separate library was the best approach. This then allows DIABAT to reside in different directories and the linking of the two codes is accomplished via library calls and separate makefiles.

IMPACT

NOGAPS is run operationally by FNMOC and is the heart of the Navy's operational support to nearly all DOD users worldwide. This work targets the next-generation of this system for massively parallel computer architectures. NSEAM has been designed specifically for these types of computer architectures while yielding the same high-order accuracy as NOGAPS.

TRANSITIONS

Improved algorithms for model processes will be transitioned to 6.4 (PE 0603207N) as they are ready, and will ultimately be transitioned to FNMOC with future NOGAPS upgrades.

RELATED PROJECTS

Some of the technology developed for this project will be used immediately to improve the current spectral transform formulation of NOGAPS in other NRL projects.

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